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NAVORD REPORT 2970

A METHOD OF MEASURING FLUX-CURRENT LOOPS OF MAGNETIC MATERIALS UNDER PULSE EXCITATION

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U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

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A METHOD OF MEASURING FLUX-CURRENT LOOPS OF MAGNETIC MATERIALS UNDER PULSE EXCITATION

Prepared by:

O. J. Van Sant, Jr. and E. D. Burnside

ABSTRACT: A simple method for obtaining the response of magnetic materials to a pulse excitation is described, and a means of determining the dynamic magnetization loop (pulse-loop) from the integration of a voltage-time curve is shown. The voltage versus time across a resistor connected in series with the magnetic core test winding is recorded photographically from a triggered cathode-ray oscilloscope trace operating at a rapid sweep rate. Equations are presented showing that the time required to switch the flux in a core material having a rectangular pulse-loop is proportional to the flux change and inversely proportional to the voltage applied to the core winding during the switching process. Curves and pulse-loops of thin-tape magnetic cores fabricated from various alloys are presented, and applications of the dynamic coercive value obtained in this measurement to circuit design are suggested.

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Since detailed information concerning the behavior of magnetic materials under pulse conditions is valuable in many ordnance applications, this method of measurement of dynamic pulse-loops of magnetic materials was developed as one phase of the development of magnetic materials and components supported by Tasks NOL-M9b-205-1-54, NOL-P4a-56-1-54, and NOL-A8-1-1-54.

This report was prepared for the information of the Bureau of Ordnance and other interested activities. It is not necessarily intended to be used as a basis for action.

A paper based on this report was presented at the Joint Meeting of the International Scientific Radio Union (URSI) and the Institute of Radio Engineers (IRE) in Ottawa, Canada on 6 October 1953.

EDWARD L. WOODYARD
Captain, USN
Commander

D S Muzzey Jr.
D. S. MUZZEY, JR.
By direction

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INTRODUCTION

1. Since the applications of magnetic materials in high-frequency or short-duration pulse circuits have increased, there is a greater need for quantitative determination of dynamic magnetic properties. Pulse transformers and digital computers employing magnetic materials are two of the more recent circuit applications of magnetic materials under pulse conditions. Dynamic hysteresis loops, as customarily displayed on the screen of a cathode-ray oscilloscope, are obtained by the use of an integrating circuit, and represent the response of the magnetic core to a sinusoidally varying emf. In certain applications, however, it is of interest to observe the response of the magnetic material to a square-step change in applied voltage, and to present the results as a flux-current pulse-loop. A simple method of obtaining such a pulse-loop is being used in the Magnetics Division to study the response of various materials at switching times of the order of magnitude of microseconds. Switching time is defined as the time required for the magnetic core material to change from negative remanence to positive saturation, or vice versa.

ANALYSIS OF FLUX CHANGES IN CORE UNDER PULSE CONDITIONS

2. Consider a toroidal magnetic core which has a fairly rectangular hysteresis loop as shown in figure 1. The magnetizing winding on the core is connected in the series circuit shown in figure 2, where R is the d-c resistance and E_o is a d-c voltage source such as a dry cell. A method of obtaining a flux-current loop from this simple series circuit is discussed in this report.

3. Assuming that a previous magnetization has left the core in a state of negative remanence ($-B_r$), and that the polarity of the battery is such that a positive magnetizing force will be applied to the core when the switch is closed, a large change of flux will result as the core goes from negative remanence to positive saturation (i.e. from $-B_r$ to $+B_m$), as shown by the heavy line in figure 3A. In this case the path of current as a function of time shown in figure 3B will be

proportional to the voltage across R. If, on the other hand, previous magnetization has been such as to leave the core at positive remanence ($+B_r$), the application of a positive current pulse to the core winding will cause only a relatively small change of flux as the core goes from positive remanence ($+B_r$) to positive saturation ($+B_m$), as shown by the heavy line of figure 4A. The current path as a function of time for this condition will resemble the curve of figure 4B. In either case the total area above the curve will represent the total flux change from the respective initial residual state.

4. After the switch is closed, the voltage drop around the series circuit is:

$$N \frac{d\phi}{dt} + IR - E_o = 0$$

where: N is the number of turns on the core

$d\phi/dt$ is the rate of change in flux in the core in webers/second

I is the instantaneous value of current in amperes

R is the value of the series resistance in ohms

E_o is the emf of the d-c source in volts

If a constant voltage E_2 is applied across a core winding of negligible d-c resistance which is wound on a core having a rectangular pulse-loop characteristic, the time Δt required to change the flux from $-\phi_m$ to $+\phi_m$ is:

$$\Delta t = \frac{N \Delta \phi}{E_2} \approx \frac{2N \phi_m}{E_2}$$

where ϕ_m is the maximum flux. Actually, the voltage across the core winding is not constant, but is equal to $E_o - IR$. However, by varying the parameters E_o and R, the switching time and the terminal point H_{max} of the flux-current loop can be varied. If the frequency associated with the switching time is well below that at which ferromagnetic resonance effects become noticeable, the coercive current will, in general, increase as the switching time decreases.

DETERMINATION OF THE DYNAMIC PULSE-LOOP

5. By feeding the voltage across the series resistor into a cathode-ray oscilloscope, both the magnetizing current

applied to the core and the rate of change of flux in the core can be found as a function of time. Since IR is the voltage drop across the resistor, and $N\frac{d\phi}{dt}$ is the voltage drop across the coil winding, the sum of IR plus $N\frac{d\phi}{dt}$ must be equal to E_o, if the distributed capacitance and leakage flux are negligible. By integrating the area above the curve in figure 5, the total flux change occurring from 0 to T_1 corresponding to H_1 at T_1 is equal to the area of the shaded portion, since

$$\int_{-\phi_r}^{\phi_1} N\frac{d\phi}{dt}\,dt = N\Delta\phi$$

At point T_1, H_1 is found from the value of current at T_1 from the expression:

$$H_1 = \frac{.4\pi N i_1}{L_m} \quad \text{oersteds}$$

where: N is the number of turns in the coil

I_1 is the current in amperes at T_1

L_m is the mean length of the magnetic path in centimeters

The change in flux density ΔB corresponding to H_1 at T_1 is:

$$\Delta B = \frac{10^8}{NA}\int_0^{T_1} e\,dt \quad \text{gauss}$$

where: $\int e\,dt$ is the shaded area above the curve from 0 to T_1 in volt-seconds; A is the cross-section area of the magnetic material in cm^2.

6. By starting at the point 0 in figure 5, we can plot successive changes in flux density with respect to $-B_r$ corresponding to values of the field H, and so obtain the portion of the loop from $-B_r$ to $+B_m$ as shown by the heavy line in figure 3A. If, after the point $+B_m$ is reached, the switch

is opened and then closed again, the flux will follow the path $+B_r$ to $+B_m$ as shown by the heavy line in figure 4A. Changes in flux density may be plotted vs H as before, using the voltage-time curve of figure 6, only in this case the changes in flux density will be with respect to $+B_r$ instead of $-B_r$. The two curves will meet at point $(+H_m, +B_m)$. The horizontal axis of the B-H loop will lie midway between $+B_r$ and $-B_r$, and the points $-B_r$ to $+B_m$ to $+B_r$ describe half of the symmetrical pulse-loop associated with a given H_m and switching time.

INSTRUMENTATION

7. The measuring circuit is shown in the block diagram of figure 7. The circuit was closed by means of a non-chattering Western Electric 218-A mercury relay switch operated by means of an external bar magnet. Connections to a Tektronix 513-D or 517 cathode ray oscilloscope were made as shown. The current in the circuit was measured by means of a precision potentiometer across a Leeds and Northrup Bureau of Standards Type 1-ohm precision resistor, R_1 in figure 7, and a Wheatstone bridge was used to measure the resistance of R_1 plus R_2 in the circuit. The final voltage across the resistors was determined by this IR product rather than from a voltmeter reading. The sweep circuit of the oscilloscope was externally triggered by means of the battery voltage E_o, firing at the close of the switch. An accurate time-base for the voltage-time curve was provided by beating the output of a General Radio 905-C signal generator against a Hewlett-Packard 100B 100-Kc crystal-controlled frequency standard on the screen of another oscilloscope, and connecting the output of the RF oscillator to the second input of the Tektronix oscilloscope. The choice of timing frequency depended upon the switching time of the core, but a 1-megacycle sine wave has been used for most of the time calibration in the measurements.

8. Photographs of the oscilloscope screen were made with a Polaroid Land oscilloscope camera operated at "bulb". The camera shutter was opened manually just before firing the triggered sweep by closing the relay switch. As the switching time of the core decreased, the rate of movement of the spot across the oscilloscope screen became too rapid to register a single sweep, and the signal was repeated from one to fifteen times at the faster sweep rates. The consistency of the input pulse was sufficient to superimpose the traces for a single line in the photograph. For example, when switching times of three microseconds or less were recorded by the Tektronix 513-D oscilloscope, even with 11,000 volts accelerating potential on the cathode-ray tube, a camera with a lens

set at f 1.9, and film with an ASA index of 100, it became necessary to repeat the sweep from ten to twenty times for a legible trace on the photograph. When the last exposure had been made for the curves, the lens opening was reduced to f 16, the shutter was opened once more, and the base line of the graph was established by moving the spot across the screen by means of the horizontal positioning control.

SUMMARY OF EXPERIMENTAL RESULTS

9. By properly varying the applied d-c voltage and the resistor in the series circuit, a family of B-H loops may be plotted for any given H_m as in figure 8. The sample used to obtain these loops was 20 turns of 5% Molybdenum Permenol ribbon wound on a .354" diameter bobbin. The width of the tape is 1/8" and the thickness is .0002". (5% Molybdenum Permenol is a magnetic alloy manufactured in the Magnetics Division and consists of 5% molybdenum, 79% nickel, and the balance iron). The loops were taken at an H_m of 1 oersted, which was obtained with a steady state current of 38.8 milliamperes through 58 turns in the magnetizing winding. E_o and R were selected to give switching times of 22.7, 4.80, 3.39, 1.87, and 1 microseconds.

10. Also shown is the d-c hysteresis loop obtained by the standard ballistic galvanometer method, except for the portion of the loop between $+B_r$ and $+B_m$, which is usually measured by traversing the portion of the loop from $+B_m$ toward $+B_r$ instead of from $+B_r$ to $+B_m$ as was done in the curve of figure 8. The dotted loops are approximations of pulse loops associated with switching times of 1 microsecond and 1.87 microseconds.

11. Measurements of the lower portions of these loops are difficult to determine accurately because of "ringing" of the vertical amplifier of the oscilloscope when employed at high sweep rates. However, the coercive force at these fast switching times may still be determined with a fair degree of accuracy since ringing occurred in the current-time curve only at values of time near $T = 0$. The values of B_m and B_r of all the solid-line curves differ by not more than 5%, which is an indication of experimental error encountered in this method of obtaining flux-current loops.

12. Figure 9 illustrates how the voltage-time curves of the different materials can vary even though E_o (3 volts) and H_m (1 oersted) are the same in all three cases. These three materials are Orthonik (50-50 nickel-iron), Alfenol (16-84 aluminum-iron) and 5% Molybdenum Permenol, respectively. The winding on each core was 58 turns. The tape thickness of the Orthonik

and Molybdenum Permenol is .0002", and that of the Alfenol is .0004". The number of turns of tape was such that the total flux change of the three core materials was approximately the same in going from $-B_r$ to $+B_m$. It is apparent from the photographs that the Molybdenum Permenol has a much smaller coercive force than the other two materials, even though its switching time is faster. Since the Molybdenum Permenol always has a smaller coercive force associated with a given switching time, the voltage drop across the series resistor will be smaller. This in turn permits a larger voltage to appear across the core winding and will result in a faster switching time because with a given flux change the switching time decreases as the voltage across the core winding increases.

APPLICATIONS AND RECOMMENDATIONS

13. Care must be taken to see that the useful part of the trace occupies the most linear portion of the cathode-ray tube screen. Enlargements of the photographs were made by tracing an enlarged image obtained by means of an opaque projector, although enlargements made from conventional film negatives are equally satisfactory. Integration of the selected area increments was made by tracing the curves on thin paper and weighing these portions of the area on a sensitive chemical balance. Since the weight per unit area of the paper had been determined previously, it became a simple matter to convert directly from grams to gauss. Integration by this method proved to be more accurate and considerably more rapid than the conventional planimeter method.

14. Practical limits to the measurement of pulse loops are determined by the ratio of H_m to the dynamic coercive force H_c. As H_c approaches H_m the voltage-time curve for the flux change from $-B_r$ to $+B_m$ becomes nearly identical with the curve for $+B_r$ to $+B_m$, as shown in figure 10A, and the difference between them becomes difficult to measure accurately. When H_c is very much smaller than H_m, the two curves will be similar to figure 10B. Here H_c is difficult to measure because the thickness of the lines is an appreciable fraction of H_c. Figure 10C illustrates the type of trace which will give the greatest accuracy in the determination of pulse loops.

15. If the distributed capacitance of the coil winding is negligible, the only upper limits to the maximum speed at which pulse-loops may be taken are the linearity and speed of the sweep circuit, and the linearity and response of the vertical amplifier of the oscilloscope to signals with extremely rapid rise times, since the flux change from $+B_r$ to $+B_m$ produces a rapid rise of current at the faster switching times.

16. By employing the simple procedure just outlined, approximate circuit parameters necessary to achieve a given switching time and H_{max} may be determined. The selection of the most appropriate material for a given application, such as a digital computer element, can be facilitated when the dynamic pulse-loop is available for detailed study. Comparative estimates of power losses of different core materials can easily be made when the dynamic coercive force associated with a given switching time for each material is known, and once the relation between the various dynamic coercive currents and switching times of a coil are known, it is possible to predict the behavior of the coil when employed as a pulse transformer.

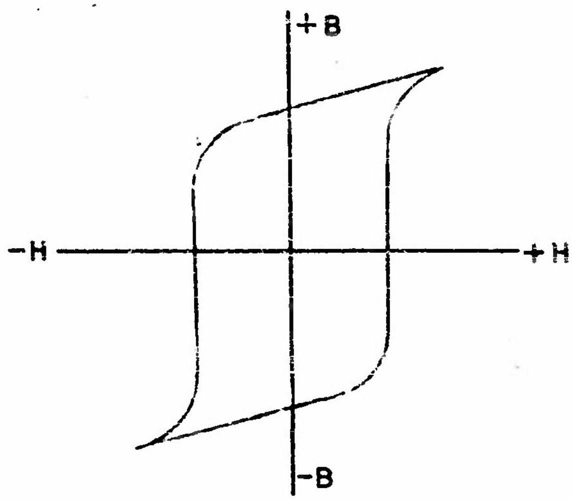


FIG. 1. TYPICAL RECTANGULAR HYSTERESIS LOOP

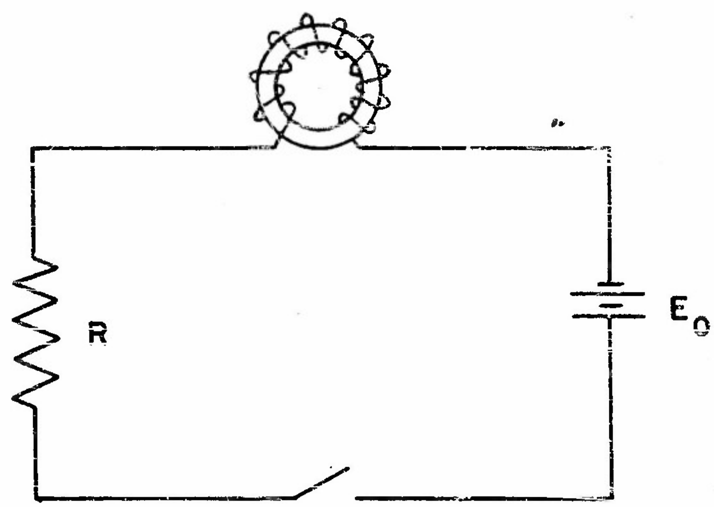


FIG. 2. SERIES TEST CIRCUIT

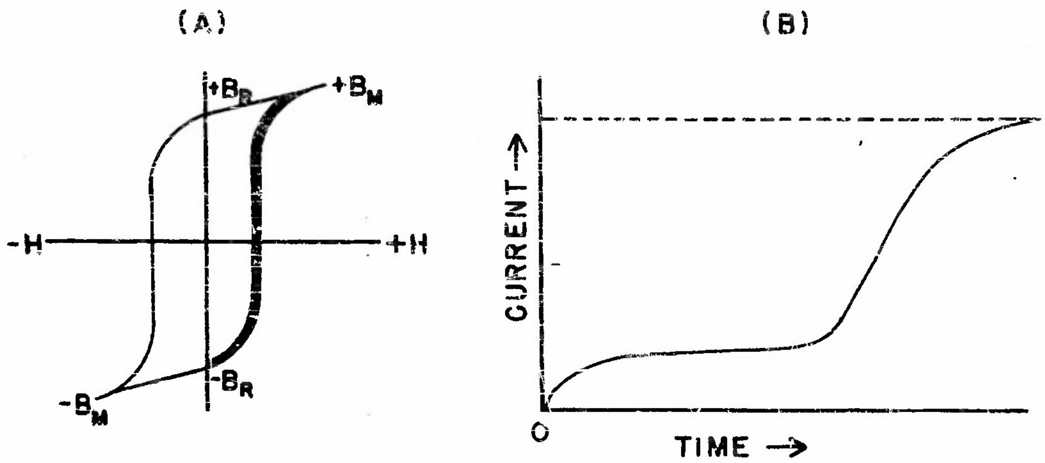


FIG. 3. CURRENT vs. TIME AS FLUX CHANGES FROM $-B_R$ TO $+B_M$

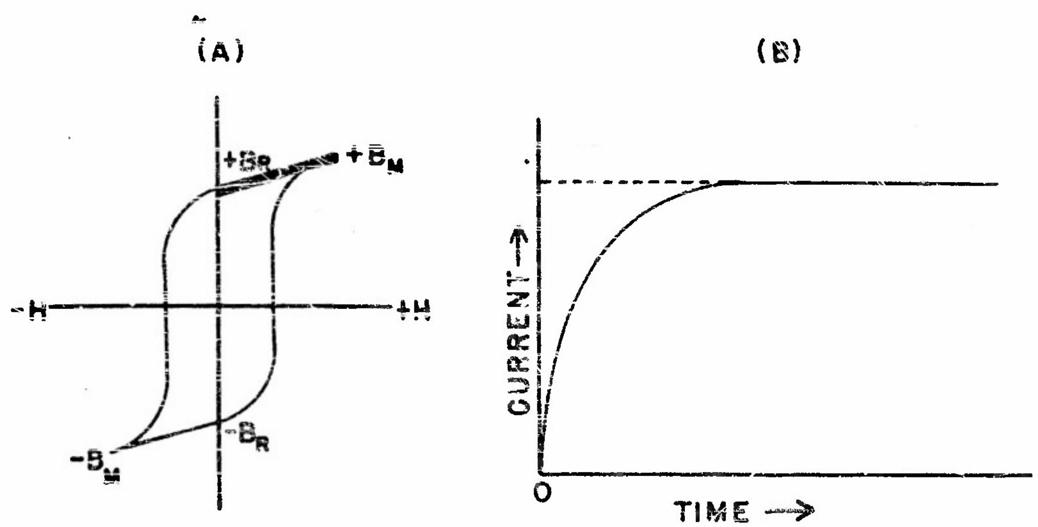


FIG. 4. CURRENT vs. TIME AS FLUX CHANGES FROM $+B_R$ TO $+B_M$

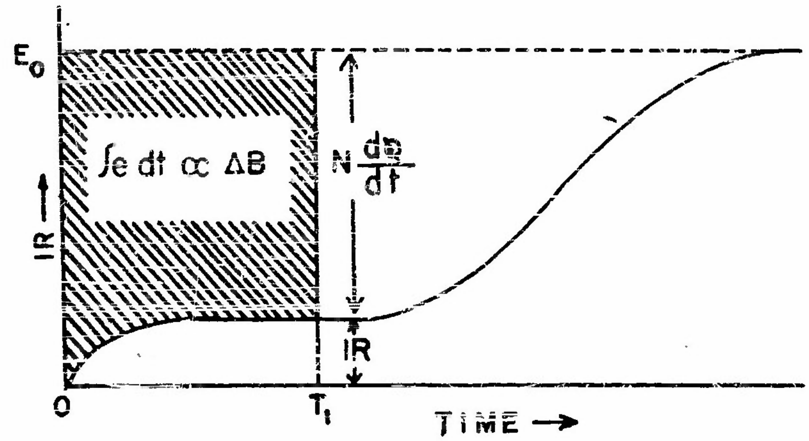


FIG. 5. VOLTAGE ACROSS SERIES RESISTOR vs. TIME AS FLUX CHANGES FROM $-B_R$ TO $+B_M$

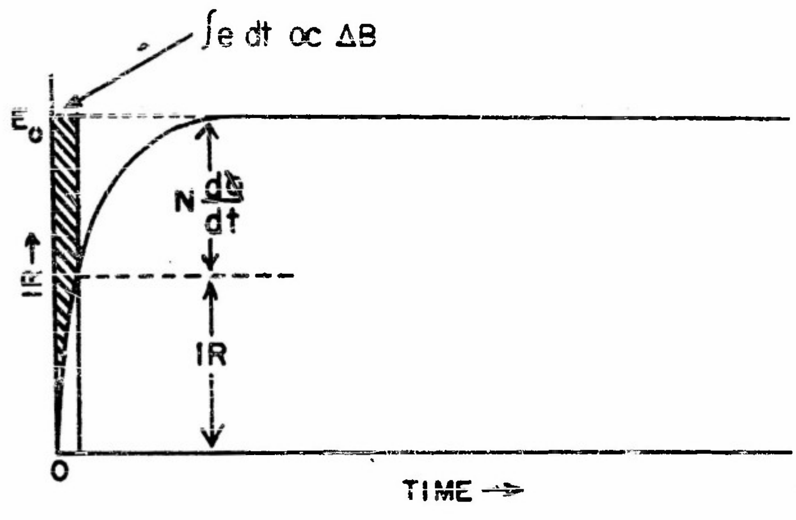


FIG. 6. VOLTAGE ACROSS SERIES RESISTOR vs. TIME AS FLUX CHANGES FROM $+B_R$ TO $+B_M$

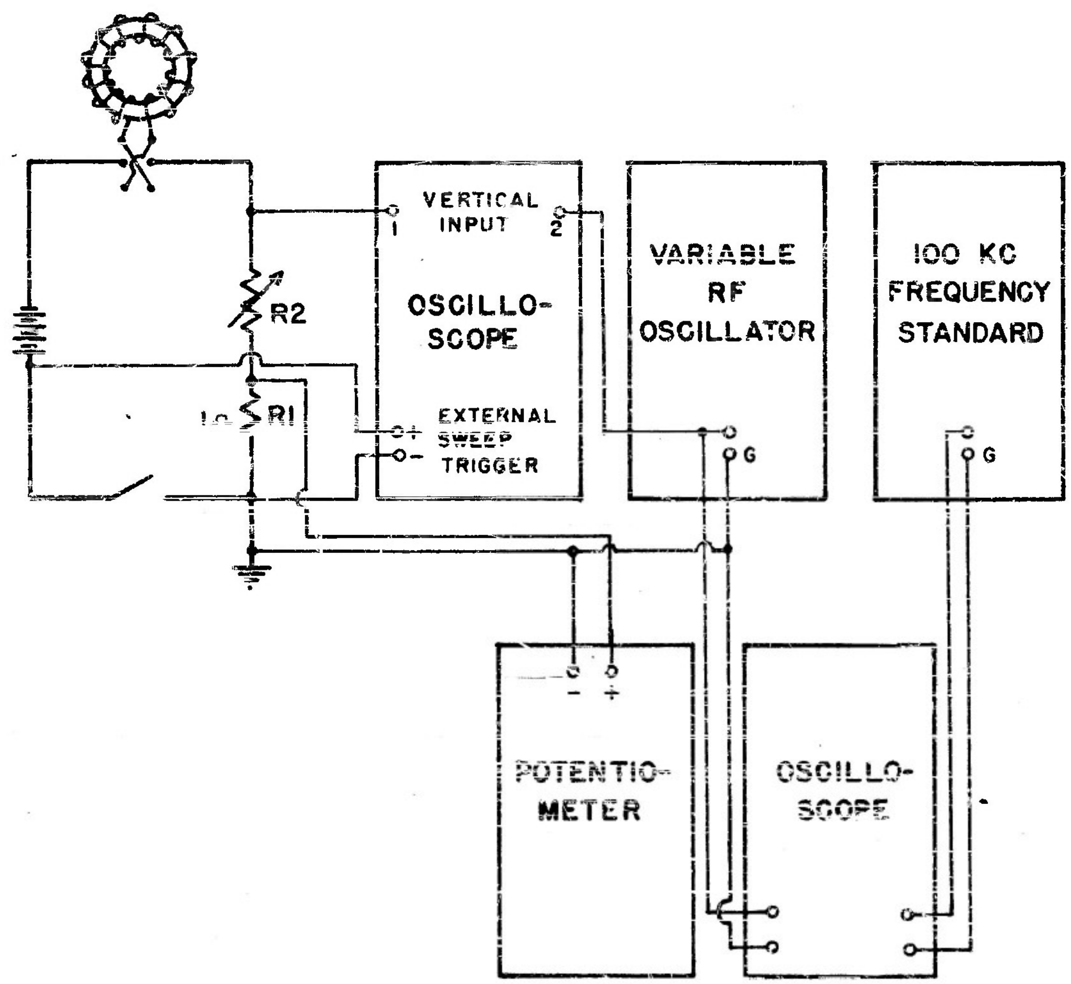


FIG. 7. BLOCK DIAGRAM OF MEASURING CIRCUIT

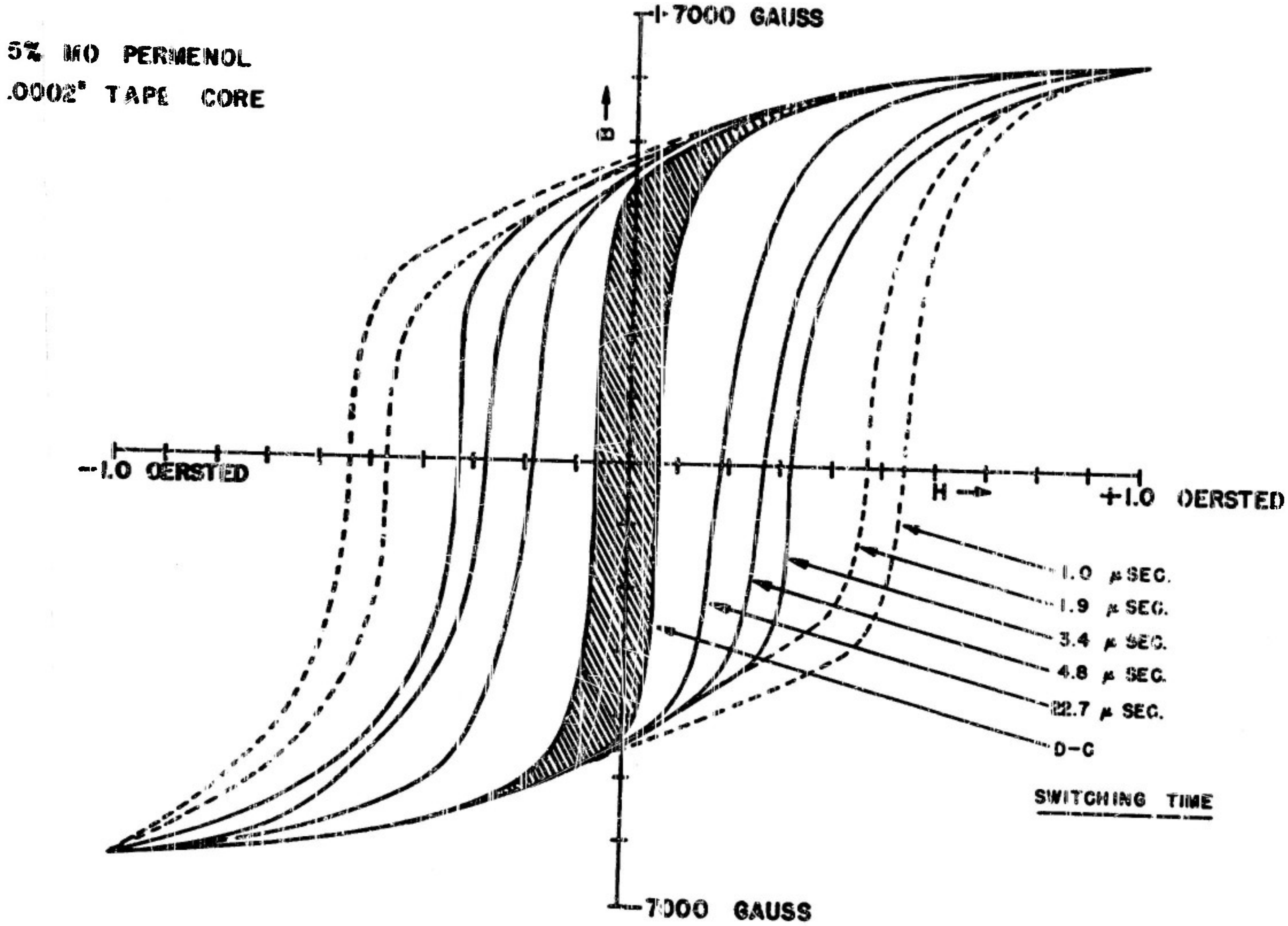
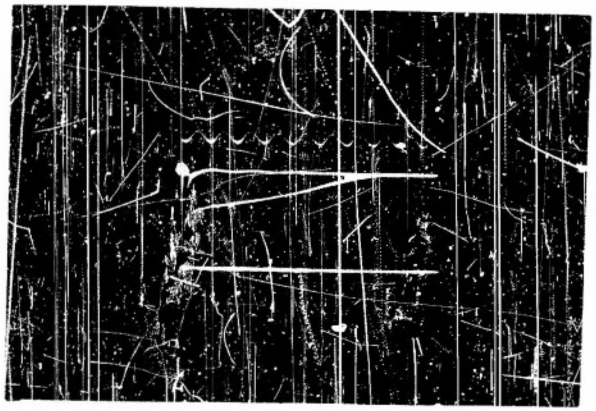
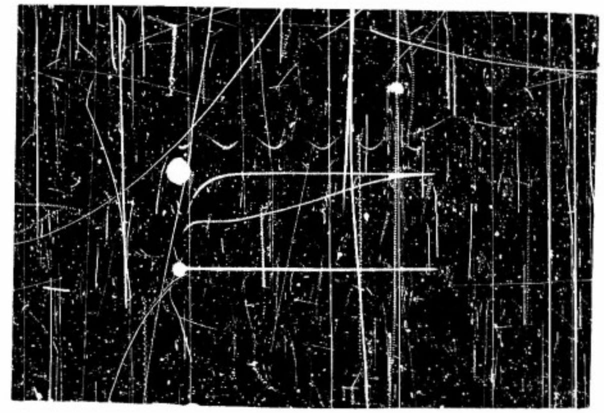


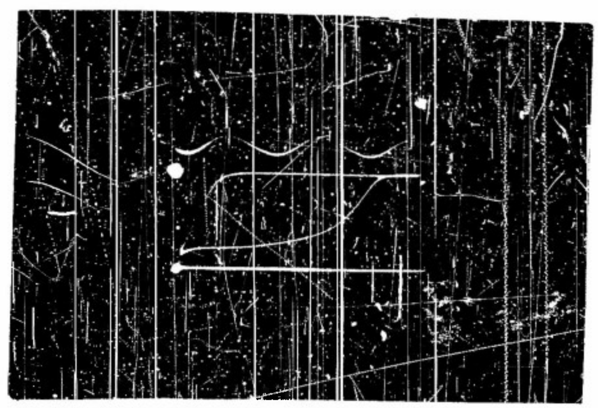
FIG. 8. FAMILY OF PULSE LOOPS



ORTHONIK



ALFENOL



5% MO PERMENOL

VOLTAGE-TIME CURVES AT 1 OERSTED, E_0 = 3.10 VOLTS, T = 200 KC

FIG. 9

FIG. 10A

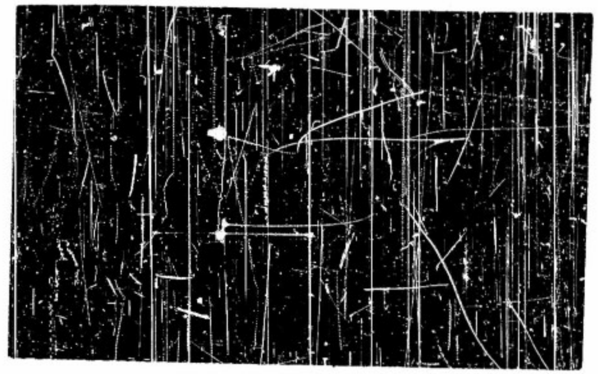


FIG. 10B

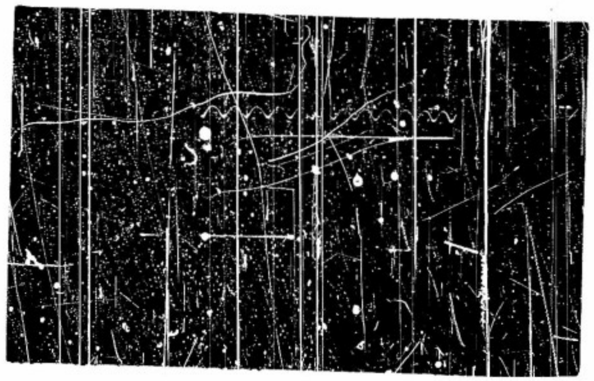


FIG. 10 C

VOLTAGE—TIME CURVES — 5% MO PERMENOL